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DESIGNING MFTF THERMAL ABSORBERS

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Summary

Both ion dumps and neutral beam dumps have been designed for the Mirror Fusion Test Facility (MFTF) at the Lawrence Livermore Laboratory. Engineering and design has been completed, and fabrication will be contracted to industrial firms in late 1979.

This paper presents the performance requirements, heat density, and heat distribution on both dumps. The thermal analysis for determining the dumps' size and methods for cooling them are discussed. Attention is also directed to mechanical design and fabrication as well as to leading-edge design and thermal panels.

Introduction

Thermal absorbers in the Mirror Fusion Test Facility include neutral-beam dumps and ion dumps. Both dumps receive a heat load from the neutral-beam injectors. During the source-conditioning mode, the magnets are not energized, and all the energy from the neutral-beam injectors is released on the neutral-beam dumps. During the experimental mode, the magnetic field is in effect. The un-neutralized portion of the neutral beam (representing one-third of the total energy from the injector) is deflected to the ion dumps. The remaining portion goes into the plasma region, from which some leaks to the neutral-beam dump.

There are 24 ion dumps in the MFTF fusion chamber, one dump for each sustaining-neutral-beam module. Each ion dump is mounted on a neutral-beam module so it will move with the module as it is being steered to aim the beam. A set of neutral-beam dumps is located in each of the four neutral-beam domes on the vacuum vessel. Cooling water is circulated to both ion dumps and neutral-beam dumps to carry the heat outside the vacuum vessel.

Performance Requirements

The ion dumps must be able to intercept the ions thrown off by the sustaining neutral beams and deflected from the beam paths by the magnetic field. The energy absorbed by the ion dumps must be transferred to the outside of the vacuum vessel before the neutral beams are fired again. All sustaining neutral beams fire at five-minute intervals for a 0.5-second pulse. The total heat deposited on each ion dump is approximately 1×10^6 J from each shot.

The neutral-beam dumps must be capable of absorbing the energy from the six sustaining neutral beams associated with each dump, and the heat must be transferred to outside the vessel within five minutes. Each neutral-beam dump will receive 18×10^6 J per shot.

Heat Load and Peak Density

The power density distribution in the beam can be characterized by a bi-gaussian, angular-power-density distribution.¹

$$P'(x_1, y_1, z) = \frac{P_0}{16 x_0 y_0} \left[\operatorname{erf}\left(\frac{x_0 + x}{2\theta}\right) + \operatorname{erf}\left(\frac{x_0 - x}{2\theta}\right) \right] \left[\operatorname{erf}\left(\frac{y_0 + y}{2\phi}\right) + \operatorname{erf}\left(\frac{y_0 - y}{2\phi}\right) \right]$$

where

P'' = power per unit area of surface normal to the Z axis at point (x_1, y_1, z) .

θ, ϕ = angles at which power flux becomes 1/e of its maximum value.

x_0, y_0 = source dimensions

The heat load on the neutral-beam dump is based on the source parameters:

$$\begin{aligned} x_0 &= 5 \text{ cm} \\ y_0 &= 22.5 \text{ cm} \\ \theta &= 0.5^\circ \\ \phi &= 1.5^\circ \\ P_0 &= 6.4 \times 10^6 \text{ W} \end{aligned}$$

At $Z = 1130$ cm where the dump is located, the maximum peak density is $P'' = 6.66 \text{ kW/cm}^2$. During the source conditioning mode, all six beams may release into their neutral-beam dump a total of 38.4 MW energy for one-half second, which is about 18×10^6 J.

The trajectory of ions leaving a beam module is calculated with the 3-D computer code GFUN. For a typical source, the ion-beam footprint is traced by starting the trajectory at nine points over a rectangular area that is characteristic of the beam size at the exit of the neutralizer and then following the mapping of the rectangular area along the curved trajectory. The power density (calculated at a plane parallel to the beam and 7.5 cm away from it) is found to be 3.5 kW/cm^2 . For a 0.5-second pulse during an experiment, about 30% of the 6.4 MW goes into the ion dump, or releases about 1×10^6 J there.

Design Approach

Designs for a heat-absorbing panel for high-energy beams have been produced by a few predecessors who have also provided evaluations for materials to be used in a thermal dump.^{2,3}

Because of its thermal properties and low cost, copper is the most favored material for a passive-cooling thermal dump.* But the copper will reach its melting point at a 5-kW/cm^2 heat load, assuming the same rate of heat transfer as in a semi-infinite slab. Therefore, the maximum heat load on copper must be limited to 4 kW/cm^2 so the surface temperature will not exceed 80% of its melting point. The time history of surface temperature on both sides of the copper can be determined by this unsteady-conduction equation in one-dimension:

$$\frac{1}{\alpha} \left(\frac{\partial T}{\partial \theta} \right) = \frac{\partial^2 T}{\partial x^2}$$

The equation above can be written as a finite-difference equation (i.e., for finite $\Delta\theta$ and Δx),

$$\frac{1}{\alpha} \left(\frac{\Delta T}{\Delta \theta} \right) = \frac{\Delta x^2 T}{\Delta x^2}$$

where the subscripts θ and x indicate whether the time, θ , or the location, x , is the variable effecting the change in T . Furthermore, one surface of the plate is in contact with a fluid whose temperature is either constant or a known function of time. Therefore, the boundary condition⁴ can be expressed by:

$$\left(\frac{\partial T}{\partial x} \right)_0^t = \frac{T_0^t - T_{00}^t}{k_s/h}$$

*The design work for the thermal absorbers was assisted by A. Riddlebarger, EG&G, San Ramon, CA.

It says, at any time $(t\Delta\theta)$, the temperature gradient at the surface $(\partial T/\partial X)_0^t$, must be equal to the temperature difference between the surface and the fluid,

$$T_0^t - T_{\infty}^t, \text{ divided by } ks/\bar{h},$$

where ks is the thermal conductivity of the solid and \bar{h} is the unit-surface conductance. A computer program was written to carry out the repeating calculation of temperature rise over time for copper plates of various thicknesses. The result is plotted in Fig. 1.

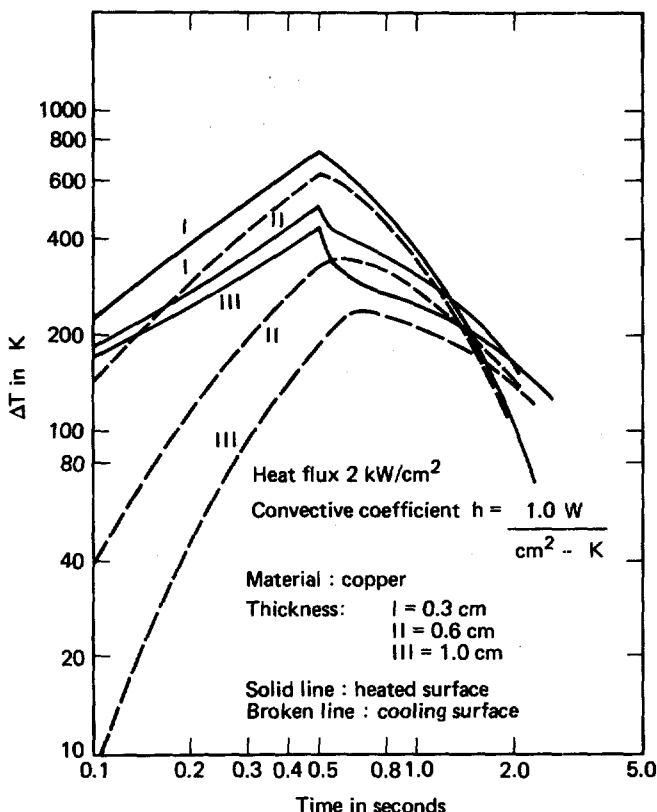


Fig. 1 Temperature rise overtime for various thicknesses of copper

Because of the compact arrangement of the neutral beam modules, there is only limited space left for the ion dump to be mounted on them. This tight spacing will not allow the ion dump to be slanted in order to reduce the heat density. Therefore the surface of the ion dump will be exposed to a 3.5 kW/cm² heat load. A 60 cm x 60 cm x 2.5 cm copper panel will cover trajectory footprints in various locations. Cooling channels are provided by twelve 1-cm-diameter holes through the plate. These twelve channels, connected by "U" tubes, are grouped into two loops. Each loop delivers 4 gpm of water. At this flow rate, the water speed in the channel is 2.9 m/s, which gives a 1 W/cm² - K convective-cooling rate and 20 psi pressure drop across the dump. The dump will be cooled off in approximately 60 seconds. Fig. 2 shows the ion dump in assembled state.

Unlike the ion dump, the neutral-beam dump can have a slanting surface to bring the heat density down. A design for a neutral-beam dump using slanted surfaces is shown in Fig. 3. It consists of an array of SPX V-shaped copper panels with rectangular cooling channels. The two sides of the panel are 42° apart, with the apex of the V facing the oncoming beam. Each panel has one cooling channel

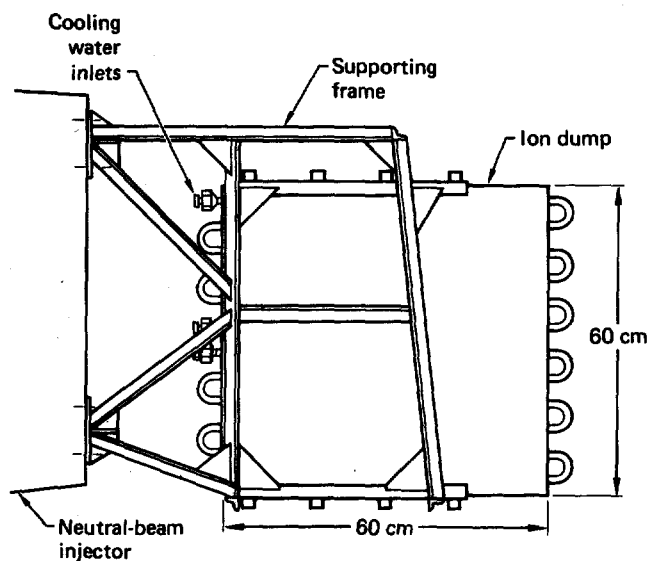


Fig. 2 Ion dump in assembled state

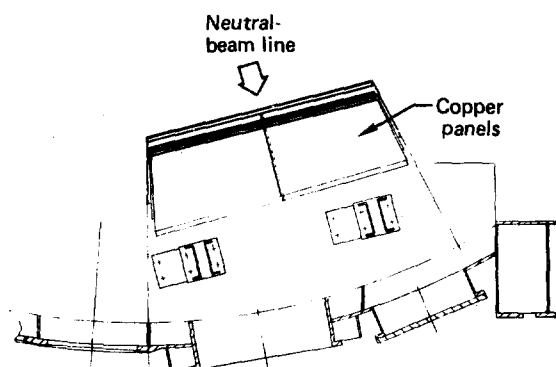
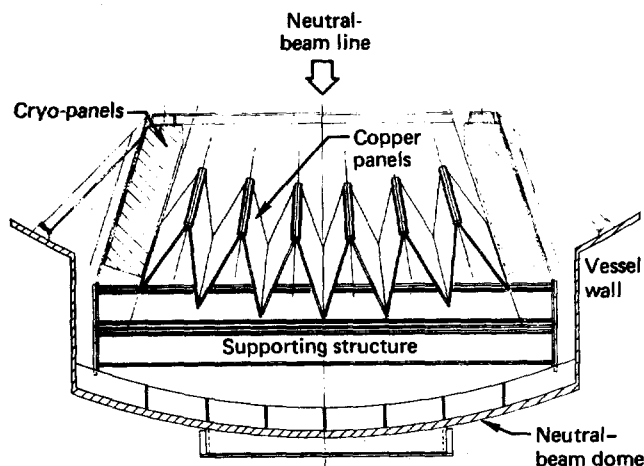


Fig. 3 Neutral beam dump

through which 2 gpm of water flows at 2 m/s. Fig. 4 shows a typical panel design. The legs of the V's are uneven, permitting an overlap to prevent the beam from shining through.

Several concepts for designing the leading edge of the V have been evaluated:

1. A tungsten tube of 6.3 cm diameter was considered. Integrating tungsten plumbing to copper tubes presents difficulties; this and the

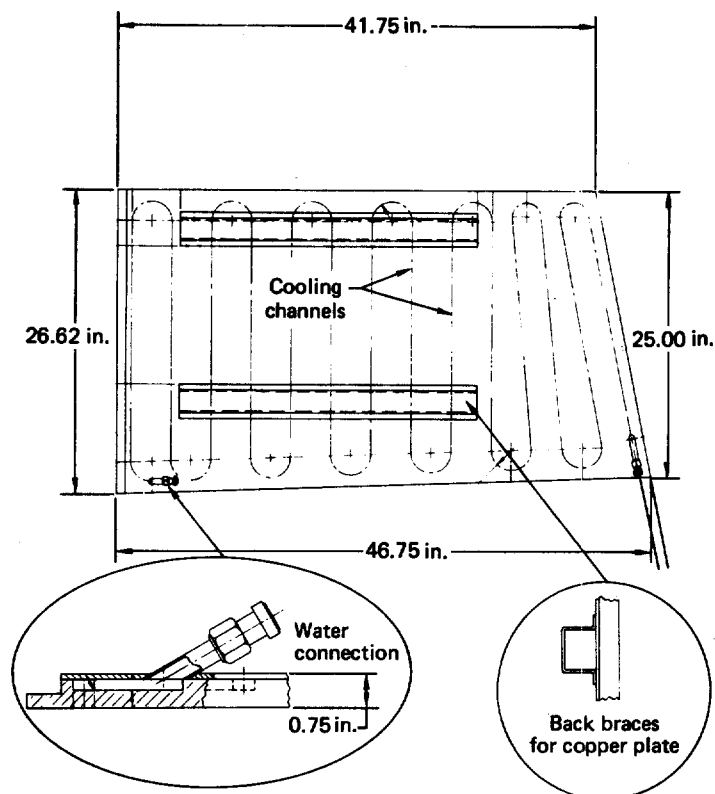


Fig. 4 Typical thermal panel design

high cost of tungsten makes this design unfeasible.
 2. Spraying a coat of tungsten over a copper tube was proposed, but industry cannot produce a sprayed coat sufficiently thick to reduce the temperature below the melting point of copper at the tungsten-copper interface.
 3. The present design uses a tungsten strip brazed to a copper plate. For a 6.6-kW/cm^2 heat load, a 0.3-cm layer of tungsten is necessary to keep the copper below its melting point. The leading edge of the panel requires cooling water. Fig. 5 shows a leading-edge design.

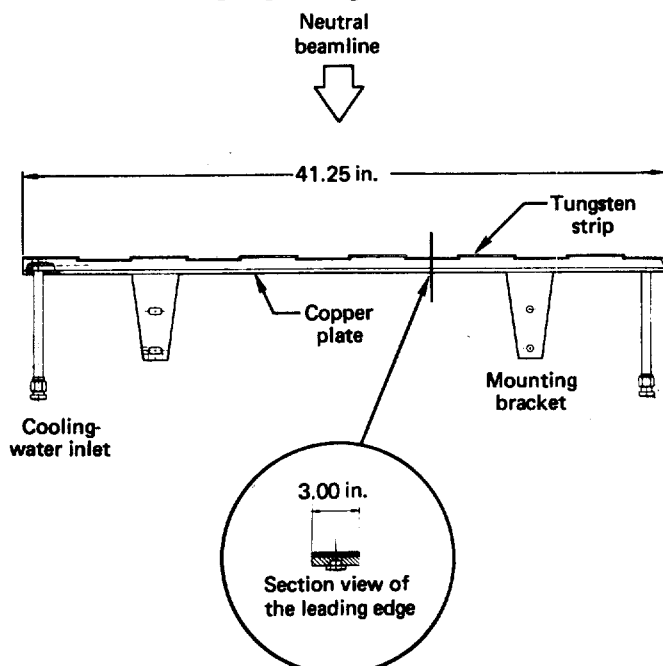


Fig. 5 Design for leading edge of thermal panel

"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48."

The neutral-beam-dump assembly is sized to cover all six sustaining beams and six start-up beams at their nominal aiming, points $\pm 4^\circ$ aiming adjustments.

Design Data Summary

Ion-Dump Design Data

Number of ion dumps in FCS	24
Total heat load per dump	$1.9\text{ MW} \times 0.5\text{ s}$
Maximum heat density on dump panel	3.5 kW/cm^2
Cooling method	passive cooling
Cooling water flow rate per panel	8 gpm
Flow speed in cooling channel	2.9 m/s
Cooling channel size	1.0 cm dia. \times 3.6 m
Dump panel material	copper
Supporting structure	S.St.
Dump size	$60\text{ cm} \times 60\text{ cm} \times 2.5\text{ cm}$
Total weight per panel	
(without structure)	75 kg
(with structure)	95 kg

Neutral-Beam-Dump Design Data

Number of dumps in FCS	4
Total heat load per dump	
(source conducting mode)	$38.4\text{ MW} \times 0.5\text{ s}$
Maximum heat density on dump panel	2.4 kW/cm^2
Maximum heat density on leaking edge	6.6 kW/cm^2
Cooling method	passive cooling
Cooling water flow rate per dump	50 gpm
Flow speed in cooling channel	2 m/s
Cooling channel size	$0.6\text{ cm} \times 1.2\text{ cm} \times 8\text{ m}$
Dump panel material	copper
Leading edge material	tungsten over copper
Supporting structure	Al 6061-T6
Dump configuration	6 "V" in line (each "V" consists of 4 panels of $76\text{ cm} \times 115\text{ cm} \times 1.9\text{ cm}$ thick)
Total weight per dump	
(without structure)	3636 kg
(with structure)	4545 kg

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